LIFETIME OF THE PRECESSION MODE OF A NANOPARTICLE MAGNETIC MOMENT IN A ROTATING MAGNETIC FIELD

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ABSTRACT

The influence of the rotating magnetic field on the thermal stability of the precession modes of the nanoparticle magnetic moment is studied analytically and numerically. The analytical results are obtained within the Fokker-Planck formalism, while the numerical ones are determined by the simulation of the stochastic Landau-Lifshitz equation. We numerically calculated the lifetime for both uniform and nonuniform precession modes, derived the expression for this time in the case of small amplitudes of the rotating field, and investigated in detail its frequency dependence.

Key words: magnetic moment, rotating magnetic field, stochastic Landau-Lifshitz equation, Fokker-Plank equation, lifetime.

INTRODUCTION

Recently ferromagnetic nanoparticles and their ensembles attract attention due to high potential of their application. In particular, two equilibrium states of the uniaxial particle magnetic moment can be utilize as a binary bit. This offers great opportunities to use such objects in modern data-storage and data-processing devices [1, 2]. One of the important issues, which stimulates the study of the magnetic moment dynamics, is the performance of such devices. It was the main motivation of many studies [3-9], where several alternative ways of switching the magnetic moment were proposed. Among them, the magnetic field that is rotated in the plane perpendicular to the nanoparticle easy axis deserves a special attention because of small switching time [9]. However, dynamics of the magnetic moment driven by such field is complex and may be nonlinear for the defined field parameters [5, 9]. That is why its study in the case of nonzero temperature is a difficult problem. But at the same time, it is promising enough in regard to identifying the new remarkable effects, such as thermal enhancement of magnetization [6], or resonant suppression of the magnetic moment stability described in the present work.

MODEL AND BASIC EQUATIONS

We suppose that the nanoparticle magnetization is characterized by vector

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m which magnitude is constant ($|\mathbf{m}| = m =$ const), but whose direction fluctuates under the action of thermal bath. The above assumption corresponds to the model of coherent rotation [10]. Only the uniaxial magnetocrystalline anisotropy defined by the anisotropy field H_a is taking into account because of the spherical shape of the particles. The **m** dynamics is described by the sto-chastic Landau-Lifshitz equation which can be written in dimensionless form as

$$\frac{d\boldsymbol{\mu}}{d\tilde{t}} = -\boldsymbol{\mu}\times(\tilde{\mathbf{H}}+\tilde{\mathbf{n}}) - \lambda\boldsymbol{\mu}\times(\boldsymbol{\mu}\times\tilde{\mathbf{H}}), \tag{1}$$

where $\boldsymbol{\mu} = \mathrm{m}/m$, $\tilde{t} = \omega_r t$ is the dimensionless time, $\omega_r = \gamma H_a$ is the Larmor frequency, $\gamma\,(> 0)$ is the gyromagnetic ratio, $\tilde{\mathbf{H}} = \partial\tilde{W}/\partial\boldsymbol{\mu}$ is the dimen-sionless effective magnetic field representing the deterministic action on m, $\tilde{\mathbf{n}}$ is the dimensionless effective magnetic field representing the random action on m, $\tilde{W} = W/mH_a$ is the dimensionless magnetic energy of the particle (W is the magnetic energy), λ (> 0) is the damping parameter. Also we imply that the oz-axis of the laboratory Cartesian coordinate system is parallel to the nano-particle easy axis. In this case the rotating field can be defined by the expression $\tilde{\mathbf{h}} = \mathbf{e}_x\tilde{h}\cos(\tilde{\omega}\tilde{t}) + \mathbf{e}_y\rho\tilde{h}\sin(\tilde{\omega}\tilde{t})$, where $\tilde{\omega} = \omega/\omega_r$ is the dimensionless field frequency, $\tilde{h} = h/H_a$ is the dimensionless field amplitude (h and ω are the amplitude and the frequency of the field, respectively), e_x, e_y are the Cartesian unit vectors, $\rho = \pm 1$ for the counterclockwise and clockwise field polarization, respectively. And finally, the dimensionless magnetic energy can be expressed as $\tilde{W} = 0.5\sin^2\theta - \tilde{h}\sin\theta\cos\psi$, where θ is the polar angle of $\boldsymbol{\mu}$, $\psi = \varphi - \rho\omega t$, φ is the azimuthal angle of $\boldsymbol{\mu}$.

From the other hand, the statistical properties of the magnetic moment can be described using the conditional probability density $P = P(\theta,\psi,\tilde{t}\,|\,\theta',\psi',\tilde{t}')$, $\tilde{t} \geq \tilde{t}'$ [11] which obeys the forward Fokker-Plank equation

$$\frac{\partial^2 P}{\partial\theta^2} + \frac{1}{\sin^2\theta}\frac{\partial^2 P}{\partial\psi^2} - \frac{\partial}{\partial\theta}\left[\cot\theta + \frac{2a}{\lambda}u(\theta,\psi)\right]P - \\ -\frac{2a}{\lambda}\frac{\partial}{\partial\psi}\left[v(\theta,\psi) - \rho\tilde{\omega}\right]P = \frac{2a}{\lambda}\frac{\partial P}{\partial\tilde{t}}, \tag{2}$$

and backward Fokker-Plank equation

$$\frac{\partial^2 P}{\partial\theta'^2} + \frac{1}{\sin^2\theta'}\frac{\partial^2 P}{\partial\psi'^2} + \left[\cot\theta' + \frac{2a}{\lambda}u(\theta',\psi')\right]\frac{\partial P}{\partial\theta'} + \\ +\frac{2a}{\lambda}\left[v(\theta',\psi') - \rho\tilde{\omega}\right]\frac{\partial P}{\partial\psi'} = \frac{2a}{\lambda}\frac{\partial P}{\partial\tilde{t}'}. \tag{3}$$

Here

$$u(\theta,\psi) = -\lambda\sin\theta\cos\theta + \tilde{h}(\lambda\cos\theta\cos\psi - \sin\psi),$$
$$v(\theta,\psi) = \cos\theta - \tilde{h}\frac{\cos\theta\cos\psi + \lambda\sin\psi}{\sin\theta},$$

$a = mH_a/2k_BT$, k_B is the Boltzmann constant, T is the temperature.

Based on the equation (2) one can transform the Landau-Lifshitz equation (1) into a system of two stochastic differential equations which are more suitable for the numerical simulation

$$\begin{cases} \dot{\theta} = u(\theta,\psi) + \dfrac{\lambda}{2a}\cot\theta + \sqrt{\dfrac{\lambda}{a}}\,\eta_\theta(\tilde{t}), \\ \dot{\psi} = v(\theta,\psi) - \rho\tilde{\omega} + \sqrt{\dfrac{\lambda}{a}}\dfrac{1}{\sin\theta}\eta_\psi(\tilde{t}), \end{cases} \tag{4}$$

where the values of $\eta_\theta(\tau)$ and $\eta_\psi(\tau)$ denote two independent Gaussian white noises with zero mean and correlation function $\langle\eta_i(\tilde{t})\eta_j(\tilde{t}')\rangle = 2\Delta\delta_{ij}\delta(\tilde{t}-\tilde{t}')$, $i, j = \theta$, ψ, $\Delta = \lambda k_BT/\gamma m$ is the random field intensity, δ_{ij} is the Cronecer symbol, $\delta(\cdot)$ is the Dirac δ function.

RESULTS AND DISCUSSION

The main characteristic of thermal stability is the lifetime $\tilde{\mathrm{T}} = \tilde{\mathrm{T}}(\theta',\psi')$, i.e., the time during which the magnetic moment stays in a given precession mode. The average value of this time was calculated using the mean first passage time method [12]. When the initial state of $\boldsymbol{\mu}$ is along the oz-axis the lifetime within this approach can be written as follows

$$\tilde{\mathrm{T}} = \int_0^\infty d\tau \int_0^{2\pi} d\psi \int_0^{\theta_0} d\theta P\left(\theta,\psi,\tau\,|\,\theta',\psi',0\right), \tag{5}$$

where $\tau = \tilde{t} - \tilde{t}'$, θ_0 is the angle of the cone surface placed well beyond the separatrix of the corresponding deterministic system. Reaching of this surface by the magnetic moment actually denotes the completion of the switching process. In the present study we assume that $\theta_0 = 0.8\pi$.

Using the backward Fokker-Planck equation (3) and lifetime definition (5), the frequency dependence of the lifetime for the uniform precessional mode was obtained in the case of $\tilde{h}a \ll 1$

$$\tilde{\mathrm{T}} = \frac{e^a}{\lambda}\sqrt{\frac{\pi}{a}}\left[1 - \frac{a\tilde{h}^2}{(1-\rho\tilde{\omega})^2 + \lambda^2 + a\tilde{h}^2}\right]\left[1 - \frac{\rho a\tilde{h}^2}{\tilde{\omega}\left(\lambda^2+\tilde{\omega}^2\right)/\left(1+2\tilde{\omega}^2\right) + \rho a\tilde{h}^2}\right]. \tag{6}$$

Depending on the direction of the field rotation $\tilde{\mathrm{T}}(\tilde{\omega})$ displays different behavior. If this direction coincides with the direction of the natural precession of the magnetic moment, then this dependence exhibits a resonance minimum.

This suggests about the resonance suppression of thermal stability of the magnetic moment by the rotating field. In other case, when these directions are opposite, the frequency dependence of the lifetime has a weak maximum. Asymptotic analysis of equation (6) shows that the lifetime does not depend on the direction of the field rotation and its value at small frequencies can be much less than at large ones.

Obtained analytical results are confirmed by the numerical simulations based on the solution of system (4) (see *Fig. 1a*). In addition, simulations let us to reveal a number of unexpected features of the lifetime of the nonuniform mode. Particularly, lifetime is practically the same as it would be expected for the uniform mode. Indeed, the long dashed curve in *Fig. 1b* ($\tilde{h} = 0.1$) covers the uniform mode only. At the same time, the short dashed curve in *Fig. 1b* ($\tilde{h} = 0.18$) covers both the uniform and nonuniform modes. This result is not obvious, because at zero temperature the time-dependences of the precession angle are different enough for these modes. It can be concluded that since the character of precession mode does not define the lifetime of this mode, the distance to the separatrix which for a given set of parameters separates one stable precession mode from the other affects this time strongly. Another feature of $\tilde{\mathrm{T}}(\tilde{\omega})$ is the dependence of the minimum location on the field amplitude that is purely nonlinear effect.

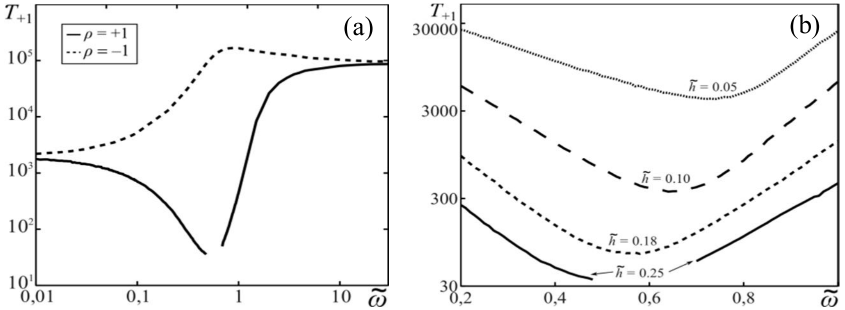

Fig. 1 – Frequency dependences of the life time for the parameters $a = 10$, $\lambda = 0.15$ (in figure (a) $\tilde{h} = 0.25$)

CONCLUSIONS

The thermal stability of the uniaxial nanoparticle magnetic moment was investigated in the term of the lifetime of the precession mode. The lifetime was studied both numerically and analytically within the mean first passage time approach. The exact analytical expression for the uniform mode lifetime in the case of small rotating field amplitude was obtained. When the direction of the field polarization coincides with the direction of the magnetic moment natural precession, the resonance suppression of thermal stability of the magnetic moment by the rotating field was revealed. The numerical calculation of the frequency dependence of the lifetime for different field amplitudes confirmed the analytical predictions and in addition showed a number of features of the nonuniform mode.

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